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Toward a Consistent Description of the PNC Experiments in A=18-21 Nuclei

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Abstract

The experimental PNC results in ^{18}F, ^{19}F, ^{21}Ne and the current theoretical analysis show a discrepancy . If one interprets the small limit of the experimentally extracted PNC matrix element for ^{21}Ne as a destructive interference between the isoscalar and the isovector contribution, then it is difficult to understand why the isovector contribution in ^{18}F is so small while the isoscalar + isovector contribution in ^{19}F is relatively large. In order to understand the origin of this discrepancy a comparison of the calculated PNC matrix elements was performed. It is shown that the ^{18}F and ^{21}Ne matrix elements contain important contributions from $3\hbar\omega$ and $4\hbar\omega$ configuration and that the $(0+1)\hbar\omega$ calculations give distorted results.

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The investigations of low energy parity nonconservation (PNC) phenomena in light nuclei have as a goal to provide more reliable results for the hadron-meson weak coupling constants. These couplings are of importance for our understanding of the quarks behavior inside the nucleons under the influence of the fundamental interactions. These investigations necessitate both very delicate experiments and very reliable nuclear structure calculations of the matrix elements for a correct extraction of the weak nucleon-meson coupling constants.

Most of the results on the experimental and theoretical PNC studies in light nuclei have been presented in the a review paper [1]. From the proposed cases during the last 25 years in this range of nuclei, four cases have been selected as reliable enough for experimental and theoretical analysis. They involve parity mixed doublets (PMD) [1] in ^{14}N, ^{18}F, ^{19}F and ^{21}Ne. Two others cases involving PMD's in ^{16}O [2] and ^{20}F [3] have been proposed recently. From the four mentioned cases, only the ^{19}F has been measured with a result larger then the experimental error. All other cases have been measured with errors larger (^{18}F and ^{21}Ne) or near the result (^{14}N). However, the absolute value of the measured errors for ^{18}F and ^{21}Ne are so small that they impose severe constraints on the different contributions to the PNC matrix elements. These results, compared to current theoretical calculation have shown a discrepancy, which has not yet been solved (see also Fig. 11 from Ref [4]). Namely, if one interprets the small limit of the (experimentally) extracted PNC matrix element (< 0.029 eV) for ^{21}Ne as a destructive interference between the isoscalar and the isovector contribution [1], then it is difficult to understand why the isovector contribution in ^{18}F is so small (< 0.09 eV) and the isoscalar + isovector contribution in ^{19}F is relatively large (0.40 ± 0.1).

In the last years, efforts have been made to improve the shell-model calculations with special emphasis on the description of the weak observables [9,10]. Recently, two new interactions have been developed by Warburton and Brown [8], which were designed to accurately describe pure $\hbar\omega$ states in nuclei with A=10-22, but methods have been developed to use them when mixed n$\hbar\omega$ excitations contribute [7,10]. Recently, we performed a (0+1+2+3+4) $\hbar\omega$ calculation in ^{14}N [7] and we obtained a PNC matrix element with a magnitude consistent with the experimental result [5,6]. These result encouraged us to look to the effect of

the higher n$\hbar\omega$ excitations for the ^{18}F, ^{19}F and ^{21}Ne cases. The previous theoretical analysis of these cases is based on the calculations of Haxton [1]: (0+1+2)$\hbar\omega$ for ^{18}F (this result was shown to be comparable with the matrix element extracted almost model independent from the first forbidden beta decay of ^{18}Ne [12]) and (0+1)$\hbar\omega$ calculations for ^{19}F and ^{21}Ne.

At present, is impossible to perform (0+1+2+3+4)$\hbar\omega$ calculations for these nuclei in the full p-sd model space or any extension of it. However, the small ZBM model space [13] contains the most important PNC transition ($1p_{1/2} - 2s_{1/2}$) and moreover, includes up to 4$\hbar\omega$ excitations. We decided to analyse the results obtained in this model space with respect to the contribution of the higher n$\hbar\omega$ excitations and to compare, when possible, with the results from the larger s-p-sd-fp model spaces. We do not expect that the absolute values obtained in this small ZBM model space to be accurate enough because we use a free space PNC potential in a severely truncated s.p. space. One would like to use an effective PNC potential, valid in a truncated model space, but this difficult problem has not been solved yet. However, we expect that the relative values of the PNC matrix elements to be significant for our analysis. Table 1 present the amplitudes of the various n$\hbar\omega$ contributions to the many body wave functions for the parity mixed doublets in A=18-21 nuclei. The calculations have been performed in the ZBM model space with the F-psd interaction [14]. One can see that in all cases the 3$\hbar\omega$ contribution is significant in all negative parity cases and 4$\hbar\omega$ contribution is relatively large for ^{18}F and ^{21}Ne. Similar magnitudes can be obtained with all the available interactions in this model space [16].

It is interesting to see if the effect of these amplitudes is reflected in the magnitude of the PNC matrix element. Table 2 presents the $n\hbar\omega \rightarrow (n+1)\hbar\omega$ decomposition of the PNC matrix elements for the above mentioned nuclei. One can observe the alternation of sign for different contributions which has been explained in Ref. [1] in a simple Nilsson quadrupole plus pairing scheme. The message of this behaviour is that one has to take into account an appropriate number of n$\hbar\omega$ in order to "smooth out" this cancelation behaviour. For instance, taking only (0+1)$\hbar\omega$ could give very distorted results due to the missing, and opposite in sign, $1 \rightarrow 2\hbar\omega$ contribution. This cancellation effect is particularly strong for

the ^{18}F and ^{21}Ne nuclei. For both those nuclei the $2 \rightarrow 3\hbar\omega$ and $3 \rightarrow 4\hbar\omega$ contributions look relatively important. Moreover, in the ^{21}Ne case the most important contribution is $1 \rightarrow 2\hbar\omega$ so that the analysis based on $(0+1)\hbar\omega$ [1] turns out to be inappropriate for ^{21}Ne.

One cannot fully verify this conclusions in a larger model space. However, one can perform some tests for ^{18}F. A calculation for the parity mixed doublet in this nucleus has been carried out using the Warburton-Brown interaction in the first four major shells including up to $3\hbar\omega$ excitations. In all these calculations: (a) the spuriousity due to the center of mass motion has been removed with the method described in Ref. [17]; (b) the effect of the short range correlations have been taken into account as described in Ref. [15]; (c) the effect of the Saxon-Woods tail of the single particle wave functions has been checked and found to be negligeable. In all our calculations we have used the DDH best values [11] for the weak coupling constants. Figure 1 presents the $n\hbar\omega$ decomposition of the wave functions and PNC matrix element calculated in the ZBM model space with the F-psd interaction. Figure 2 presents the same quantities calculated in the larger model space described above. One can see that up to 20% the contributions looks relatively similar. These give us some confidence that the small model space calculations contains the most important trends necessarily for the analysis of the PNC matrix elements in light nuclei. Certainly, one cannot rely on the absolute values given by this calculations but they put in evidence the most important features involved and they could indicate the way to improve them.

As we already mentioned, the smallness of the PNC matrix element for ^{21}Ne has been interpreted as a cancellation between the isoscalar and isovector contribution when only the $(0+1)\hbar\omega$ calculation is taken into account. We have already seen that the ZBM calculations indicate that the $1 \rightarrow 2\hbar\omega$ contribution is the most important one for this case. Table 3 presents the isoscalar-isovector decomposition of the PNC matrix elements for these nuclei. One can see that the isovector contribution is very stable in all these cases. On the other hand, the isoscalar contribution in the ^{21}Ne case is small and fluctuates around a zero value. This fact, correlated with the smallness of the pion weak coupling constant as deduced from the ^{18}F experiment [1,4], can explain the smallness of the PNC matrix element for

^{21}Ne as due to a very suppressed isoscalar contribution. A rather different conclusions has been presented in Ref. [18], where the isoscalar contribution is stable and the isovector contribution fluctuates. Their results do not offer any explanation of the smallness of the PNC matrix element. A similar conclusion to ours has been recently presented in Ref. [19].

One can go a step further in the analysis of all A=18-21 results using a graphical picture, similar to Fig. 11 from Ref. [4]. One can write the PNC matrix element for all these cases in terms of the isoscalar (IS) and isovector (IV) contributions calculated with some "standard" weak coupling constants (DDH best values in our case) and some weighting factors, $\alpha_{IS(IV)}$ and $\beta_{IS(IV)}$

$$< V_{PNC} >= \alpha_{IS} \cdot \beta_{IS} < V_{PNC}^{DDH}(IS) >_{ZBM} + \alpha_{IV} \cdot \beta_{IV} < V_{PNC}^{DDH}(IV) >_{ZBM} \quad . \qquad (1)$$

We note that the IS matrix element is dominated by the ρ exchange term proportional to h_ρ° and the IV matrix element is dominated by the π exchange term proportional to f_π [1,15]. The β factors take into account the renormalization effects due to the orbitals missing in the ZBM model space. Our assumption is that if we use the same interaction in the ZBM model space the β_{IS} and β_{IV} factors will be practically the same for all three nuclei (^{18}F, ^{18}F and ^{21}N). The results presented in Fig. 3 are based on the F-psd interaction [14]. A value of $\beta_{IV} = 0.59$ can be obtained from the comparison with the $^{18}Ne \rightarrow {}^{18}F$ first forbidden beta decay result [4]. A value of $\beta_{IS} = 0.48$ was estimated from a comparison with a recent (0+1+2+3+4)$\hbar\omega$ calculation [7] in ^{14}N. The α factors represent the ratio of the actual weak coupling constants to the DDH best values [11]. An ($\alpha_{IS},\ \alpha_{IV}$) plot, similar to that in Fig. 11 from Ref. [4] is presented in Fig. 3; it shows an overlapping region for the ^{18}F, ^{19}F and ^{21}Ne data. The ($\alpha_{IS},\ \alpha_{IV}$) values in the overlapping region are in the range (0.6-1.2, 0.07-0.26). (If one extrapolates this analysis as in Ref. [19] and assumes that the isoscalar matrix element is compatible with zero one can conclude that the ^{21}Ne experiment has measured, in fact, an isovector matrix element. This could impose smaller limits limits on the pion weak coupling constants than the ^{18}F experiment.)

In conclusion, we have theoretically analysed the PNC experiments in A=18-21 nuclei

using the small ZBM model space but looking closely to the n$\hbar\omega$ contributions. We concluded that at least for ^{18}F and ^{21}Ne it is necessary to estimate at least the effect of 3 and 4 $\hbar\omega$ contributions. The present analysis suggests that the usual interpretation of the smallness of the ^{21}Ne matrix element due to a cancellation between the IS and IV contribution, which was obtained in a (0+1)$\hbar\omega$ calculation, has to be modified due to the apparently strong $1 \rightarrow 2\hbar\omega$ contribution. We find that the possible interpretation is based on a very small IS part of the PNC matrix element, due to the nuclear structure involved, and the smallness of the IV part, due to the small pion weak coupling constant. Our analysis show that a consistent understanding of the PNC experiments in A=18-21 nuclei is possible if one include the appropriate number of n$\hbar\omega$ excitations in the nuclear structure calculations.

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Table captions

Table 1 The amplitudes of the n$\hbar\omega$ excitations to the many body wave functions for the parity mixed doublets in A=18-21 nuclei.

Table 2 Partial contributions to the PNC matrix elements in A=18-21 nuclei. Units are eV. F-psd and Z-psd interactions are taken from Ref. [14] and ZBMO interaction from Ref. [16]. Here and in the following calculations the DDH best values have been used as weak coupling constants.

Table 3 Isoscalar (IS) and isovector (IV) contributions to the PNC matrix elements in A=18-21 nuclei.

Figure captions

Figure 1 Wave function amplitudes and partial contributions to the isovector PNC matrix element (eV) for ^{18}F. Calculations have been carried out in the small ZBM model space with the F-psd interaction.

Figure 2 Same as Fig. 1 but in a larger single particle space (first four major shells) using the Warburton-Brown interaction [8]. Only (0+1+2+3)$\hbar\omega$ excitations have been allowed to contribute. The ? indicates uncalculated quantities

Figure 3 Analysis of the PNC result for ^{18}F, ^{19}F and ^{21}Ne using Eq. (1) and ZBM F-psd calculations. Solid lines represent the limits imposed by the experimental errors. Doted line is the experimental result for ^{19}F. Shadowed region indicates the consistency of the experimental result with the present analysis.

Nucleus	$J^\pi T$	0 $\hbar\omega$	1 $\hbar\omega$	2 $\hbar\omega$	3 $\hbar\omega$	4 $\hbar\omega$
	0^+1	0.443		0.424		0.133
^{18}F						
	0^-0		0.739		0.261	
	$\frac{1}{2}^+\frac{1}{2}$	0.618		0.333		0.049
^{19}F						
	$\frac{1}{2}^-\frac{1}{2}$		0.701		0.299	
	1^+1	0.637		0.326		0.036
^{20}F						
	1^-1		0.800		0.200	
	$\frac{1}{2}^+\frac{1}{2}$	0.463		0.422		0.115
^{21}Ne						
	$\frac{1}{2}^-\frac{1}{2}$		0.697		0.303	

Table 1.

Nucleus	Interaction	ΔT	$0\hbar\omega$- $1\hbar\omega$	$2\hbar\omega$- $1\hbar\omega$	$2\hbar\omega$- $3\hbar\omega$	$4\hbar\omega$- $3\hbar\omega$
^{18}F	F-psd	1	1.045	-0.815	0.549	-0.187
	Z-psd	1	1.119	-0.778	0.462	-0.148
	ZBMO	1	1.297	-0.669	0.430	-0.118
^{19}F	F-psd	0	0.566	-0.097	0.227	-0.073
		1	0.744	-0.212	0.221	-0.032
	Z-psd	0	0.633	-0.134	0.184	-0.055
		1	0.858	-0.164	0.187	-0.023
^{20}F	F-psd	0	0.473	-0.026	0.099	-0.018
		1	0.806	-0.261	0.195	0.018
	Z-psd	0	0.446	-0.086	0.037	-0.007
		1	0.762	-0.222	0.108	0.002
^{21}Ne	F-psd	0	0.290	-0.370	0.139	-0.172
		1	-0.164	0.558	-0.095	0.257
	Z-psd	0	0.404	-0.348	0.092	-0.076
		1	-0.246	0.555	-0.053	0.103

Table 2.

Nucleus	Interaction	IS	IV	Total
	F-psd	-	0.592	0.592
^{18}F	Z-psd	-	0.734	0.734
	ZBMO	-	0.794	0.794
	F-psd	0.627	0.722	1.349
^{19}F	Z-psd	0.629	0.858	1.487
	F-psd	0.518	0.757	1.262
^{20}F	Z-psd	0.389	0.650	1.032
	F-psd	-0.113	0.556	0.442
^{21}Ne	Z-psd	0.071	0.359	0.430
	ZBMO	-0.010	0.339	0.329

Table 3.

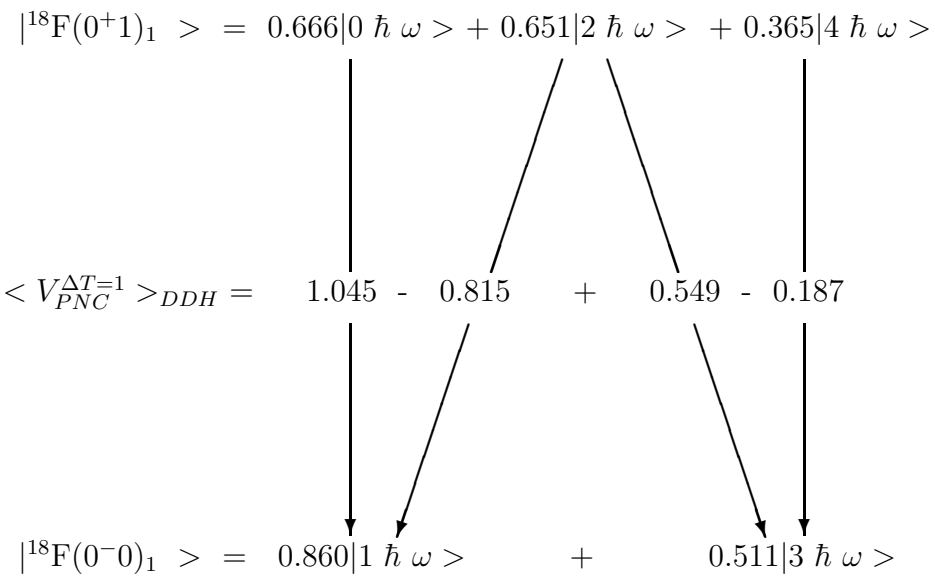
$|^{18}\mathrm{F}(0^+1)_1 > = 0.666|0\ \hbar\ \omega > + 0.651|2\ \hbar\ \omega > + 0.365|4\ \hbar\ \omega >$
$< V_{PNC}^{\Delta T=1} >_{DDH} = 1.045 - 0.815 + 0.549 - 0.187$
$|^{18}\mathrm{F}(0^-0)_1 > = 0.860|1\ \hbar\ \omega > + 0.511|3\ \hbar\ \omega >$

Figure 1.

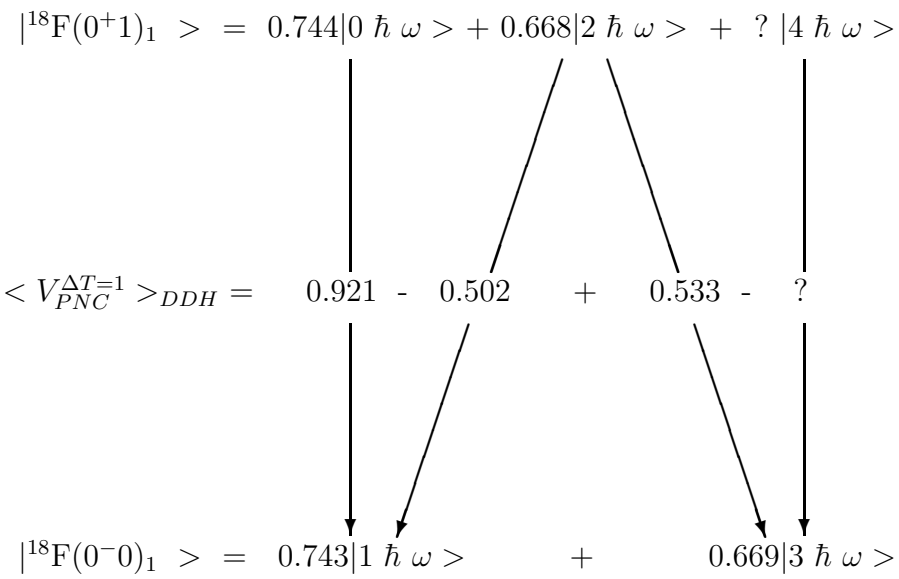
$|^{18}\mathrm{F}(0^+1)_1 > = 0.744|0\ \hbar\ \omega > + 0.668|2\ \hbar\ \omega > + ?\ |4\ \hbar\ \omega >$
$< V_{PNC}^{\Delta T=1} >_{DDH} = 0.921 - 0.502 + 0.533 - ?$
$|^{18}\mathrm{F}(0^-0)_1 > = 0.743|1\ \hbar\ \omega > + 0.669|3\ \hbar\ \omega >$

Figure 2.

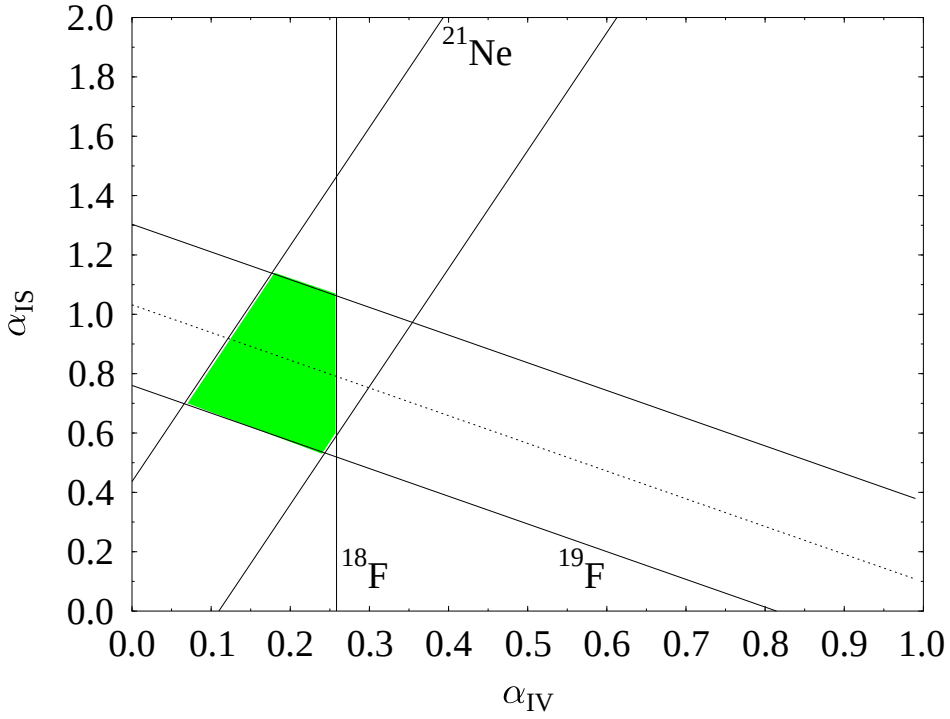
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\alpha_{\rm IS}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\alpha_{\rm IV}$
^{21}Ne
^{18}F
^{19}F

Figure 3.